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Simulating electromagnetic cascades in AGN-magnetospheres

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Conventional jet-scenarios are threatened by IC 310 and Mrk 501

Recently, the peculiar radio-galaxy IC 310 has shown extreme flux variations (Fig. 1) with time-scales of about 5min at TeV-energies. This is evidence of emission-regions of length-scales below r_g and thus cannot be explained by shock-in-jet models [1].

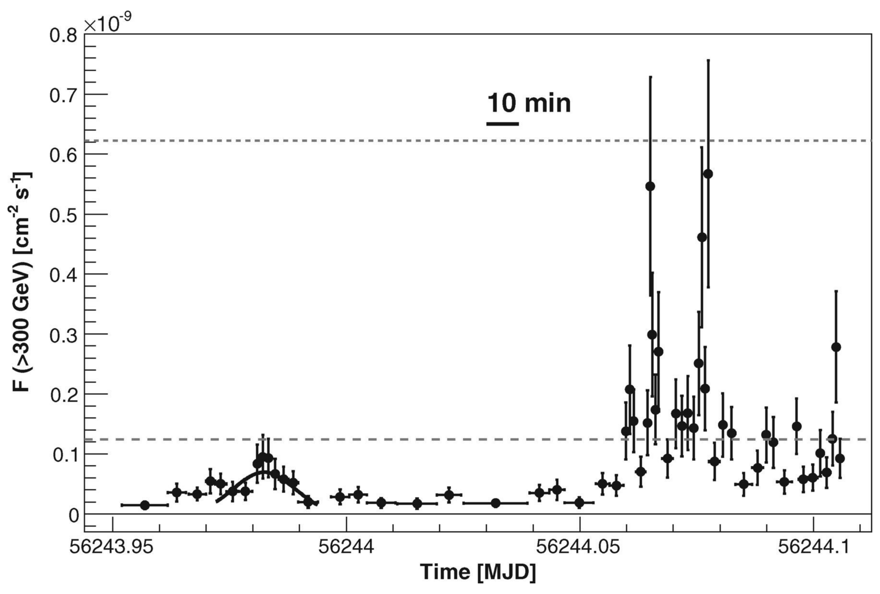

Fig. 1: IC 310's light-curve above 300 GeV, detected by the MAGIC-telescopes on 12./13. 11. 2012. [1]

Moreover, a very narrow, TeV-bump (Fig. 3b) observed in the SED of the HBL Mrk 501 by the MAGIC-telescopes in June 2012 cannot be explained by conventional models [2].

Are vacuum gaps the enigmatic machines?

Alternative models for understanding the origin of gamma-ray emission are magnetospheric models. According to these, charge-depleted regions (vacuum gaps) in AGN-magnetospheres are the birthplace of the highest-energetic particles (both UHE-cosmic rays and GeV- to TeV-photons). These gaps are expected to be located in the magnetosphere's polar regions and permeated by electric and magnetic fields [3], giving rise to particle acceleration up to ultrahigh energies and photon emission [4, 5]. Subsequently, an electromagnetic cascade develops.

Electromagnetic cascades

Particles, that intrude into the gap, are accelerated to high energies and act as seed particles for the development of an electromagnetic cascade (Fig. 2) via inverse-Compton-upscattering soft background-photons (which may stem from the accretion disk or from photo-ionised clouds). By this, HE-photons are created, which, in addition to injected HE-photons (which may stem e. g. from pion-decay), can again pair-produce new particles via interaction with the soft background-photons and thus sustain the cascade.

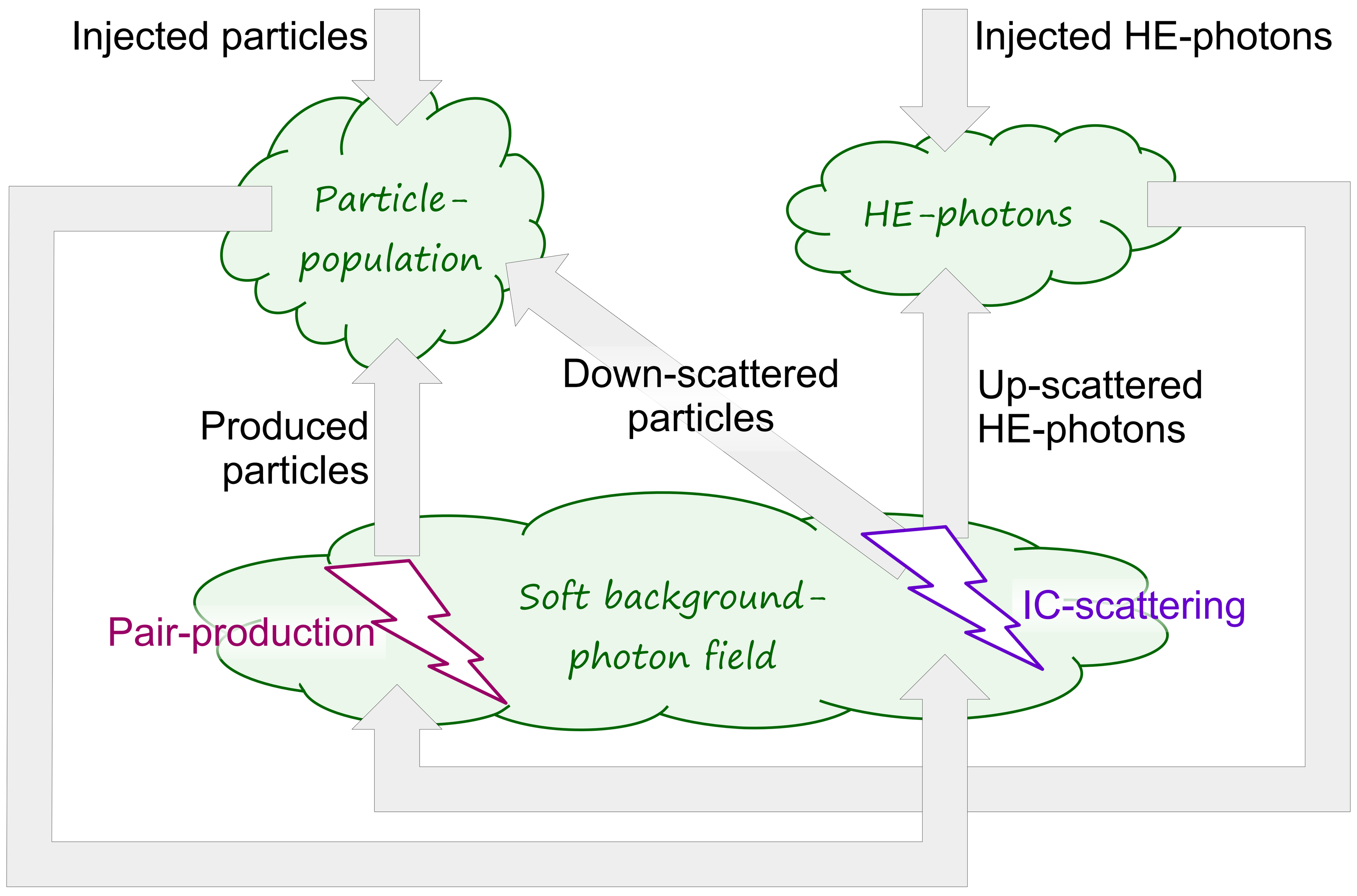

Fig. 2: Sketch of a saturated electromagnetic cascade

Numerical solution of the cascade equation

Involving pair-production and IC-scattering in the Klein-Nishina-regime, the steady-state particle-distribution $N(\gamma)$ is described by the following integral equation [6]:

$n_0(x)$

$\dot{N}_i(\gamma)$ $\quad C(\gamma,\gamma')$ $\quad p(x_\gamma,\gamma)$ $\quad \dot{n}_i(x_\gamma)$

$$\boxed{\begin{aligned} 0 = \dot{N}_i(\gamma) - N(\gamma)\int_1^{\gamma} C(\gamma,\gamma')\,d\gamma' + \int_{\gamma}^{\infty} N(\gamma')C(\gamma',\gamma)\,d\gamma' + \\ + \int_{\frac{\gamma}{1-\frac{1}{4\gamma x_0}}}^{\infty} p(x_\gamma,\gamma)\left[\int_{\frac{x_\gamma}{2}\left(1+\sqrt{1+\frac{1}{x_0 x_\gamma}}\right)}^{\infty} C(\gamma',\gamma'-x_\gamma)N(\gamma')\,d\gamma' + \dot{n}_i(x_\gamma)\right]dx_\gamma \end{aligned}}$$

$N(\gamma)$

Firstly, after specifying the input functions (distributions of soft photons $n_0(x)$, injected HE-photons $\dot{n}_i(x_\gamma)$ and injected particles $\dot{N}_i(\gamma)$), the interaction-probabilities (kernels $C(\gamma,\gamma')$ and $p(x_\gamma,\gamma)$ of the integral equation) for IC-scattering and for pair-production have to be yielded via numerical integration of the double-spectral interaction-probabilities. Secondly, the integral equation can be solved iteratively. In this way, the steady-state particle-distribution $N(\gamma)$ in the Klein-Nishina-regime and the HE-photon-distribution $n(x_\gamma)$ are yielded. Next, to determine the particle-distribution in the Thomson-regime, a continuity-equation has to be solved. As a by-product the IC-upscattered HE-photons (green term above) are yielded.

Dissecting Mrk 501

We have developed a python-code, that is able to execute the described algorithm. In the case of Mrk 501 one can assume 1.8TeV-electrons (produced in a gap) as $\dot{N}_i(\gamma)$ and Ly-α-photons (from an ionised cloud) as $n_0(x)$. These species interact in the jet of Mrk 501 via the described cascade. The solution $N(\gamma)$ converges after approx. 20 iterations (Fig. 3a). The emerging HE-photon distribution is producing the bump on top of the SSC-background (which explains X-ray and γ-ray data as well) in the Mrk 501-spectrum (Fig. 3b).

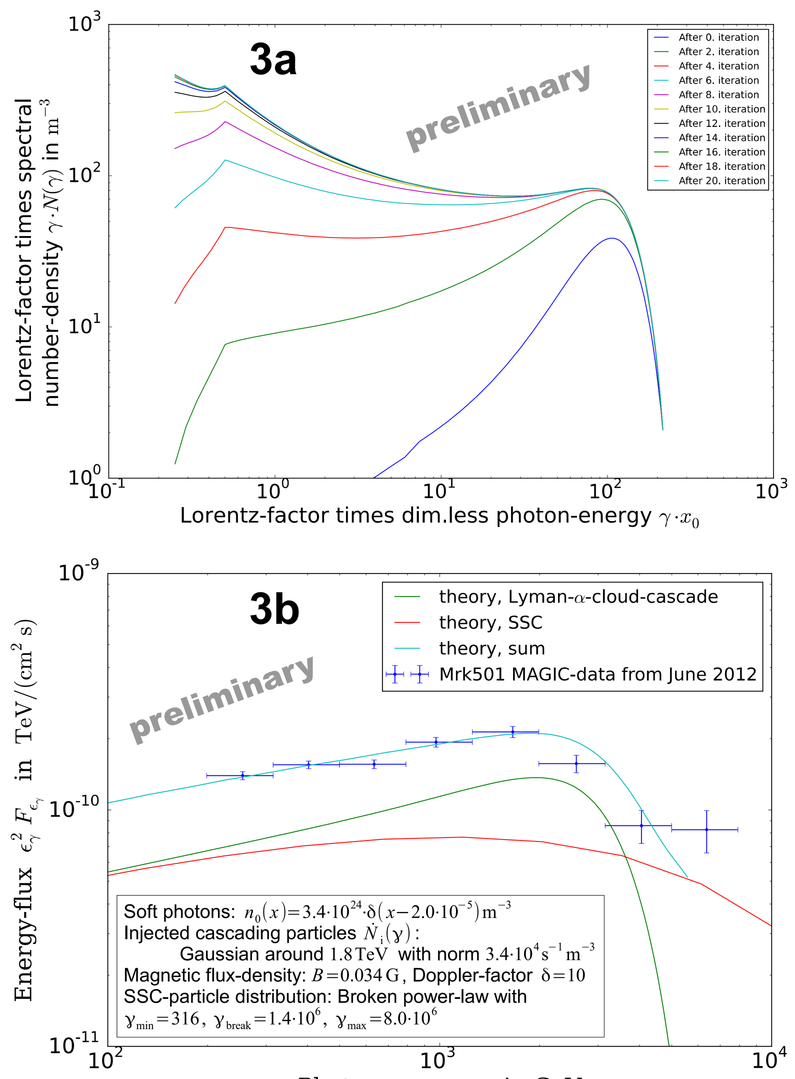

Fig. 3: Spectra of „Lyman-α-cloud"-cascade in Mrk 501:
a: Iteration of particle-distribution
b: HE-photon-distribution (data points taken from [2]) as superposition of cascade- and SSC-emission

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